Color… part 1

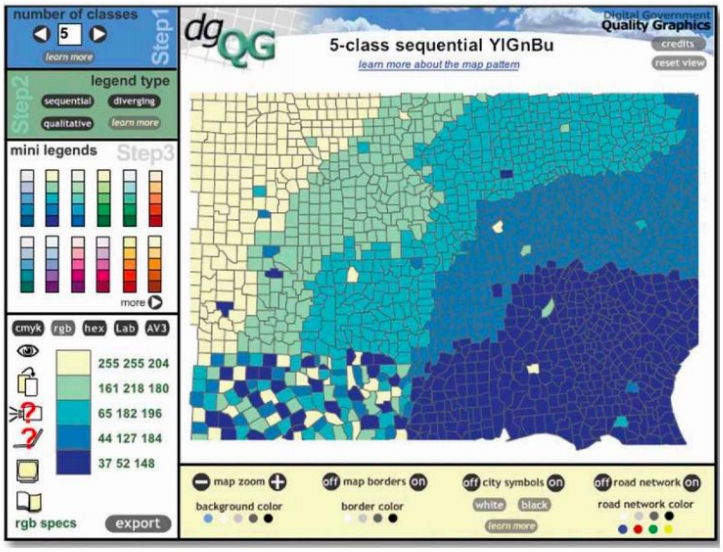
(some slides from Fredo Durand)

Today's Class

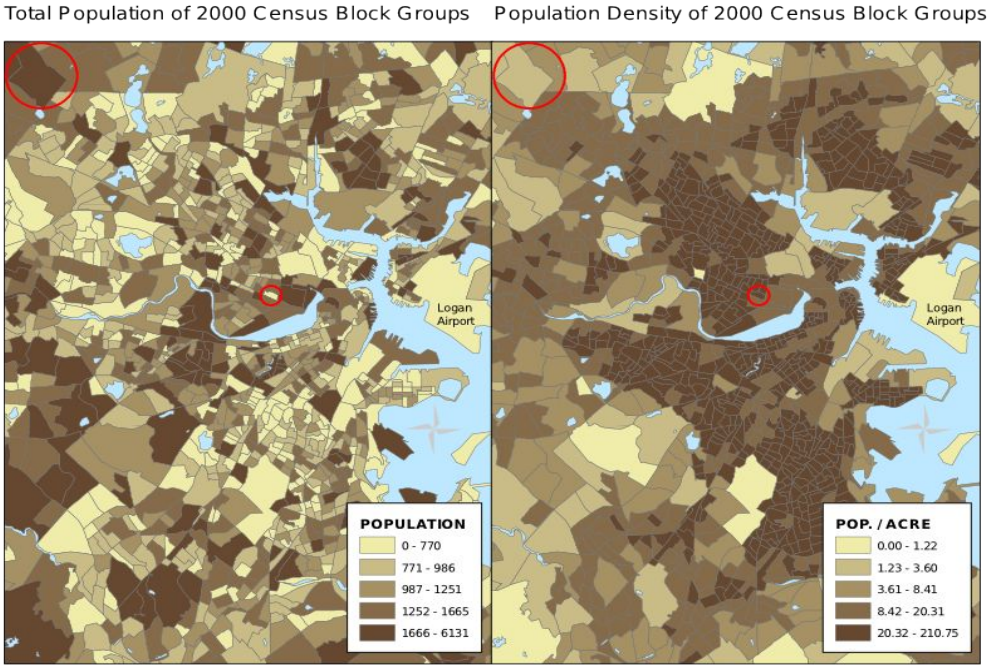
- Reading for Today
- What is Color?
  - Human Perception
  - Color Blindness & Metamerism
- Color Spaces
  - LMS, RGB, XYZ, HSV, L*a*b*, ….
- Reading Choice for Tuesday
- Color & Projection in Spatially Augmented Reality

Reading for Today

- "ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps", Harrower & Brewer, The Cartographic Journal, 2003.



Choropleth map: statistics per area
must be careful about normalization



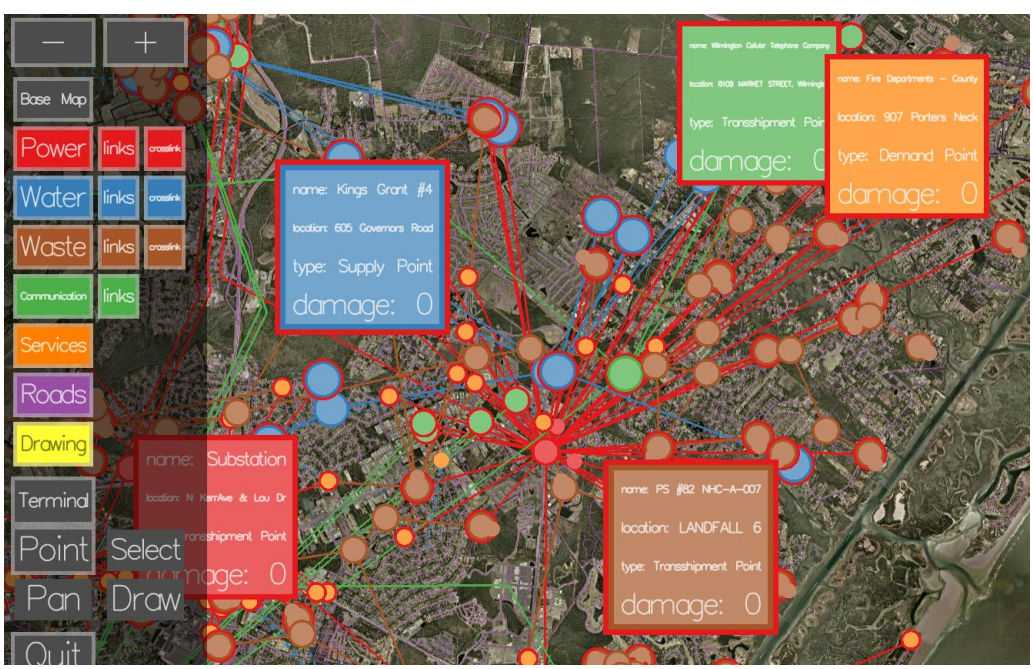
https://en.wikipedia.org/wiki/Choropleth_map#/media/File:Choropleth-density.png

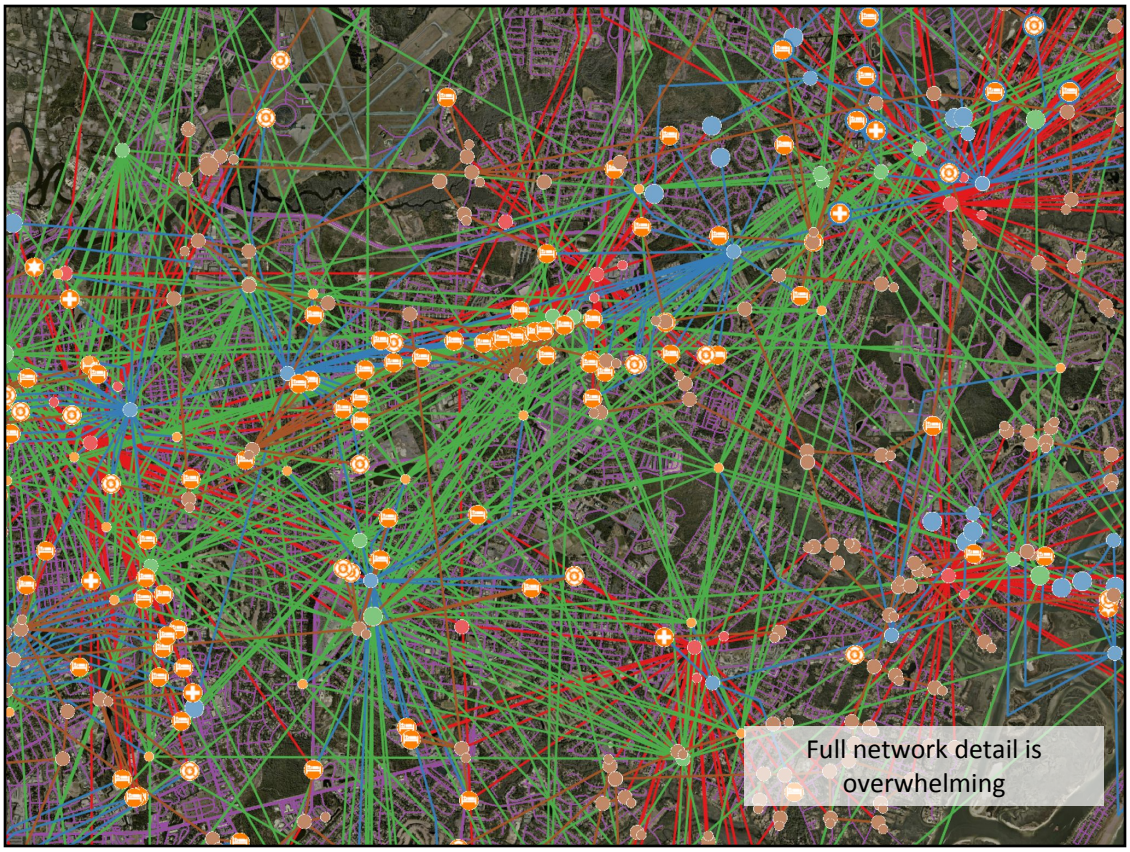
- Color selection is not one size fits all
  - don't always use the same color theme
  - don't always use the default
- Many options in map making programs
  - No guidance about choosing color schemes
  - Don’t tell them what to do, but allow them to explore options
- Standard (cartographic) conventions
  - Variations in lightness are interpreted as ordering
  - Dark equals more, light equals smaller values
  - No more than 7 colors in a choropleth map (Legibility vs. information rich tradeoff)
- Just because you can see differences doesn’t mean you can correlate color back to legend
- Important to consider borders & backgrounds

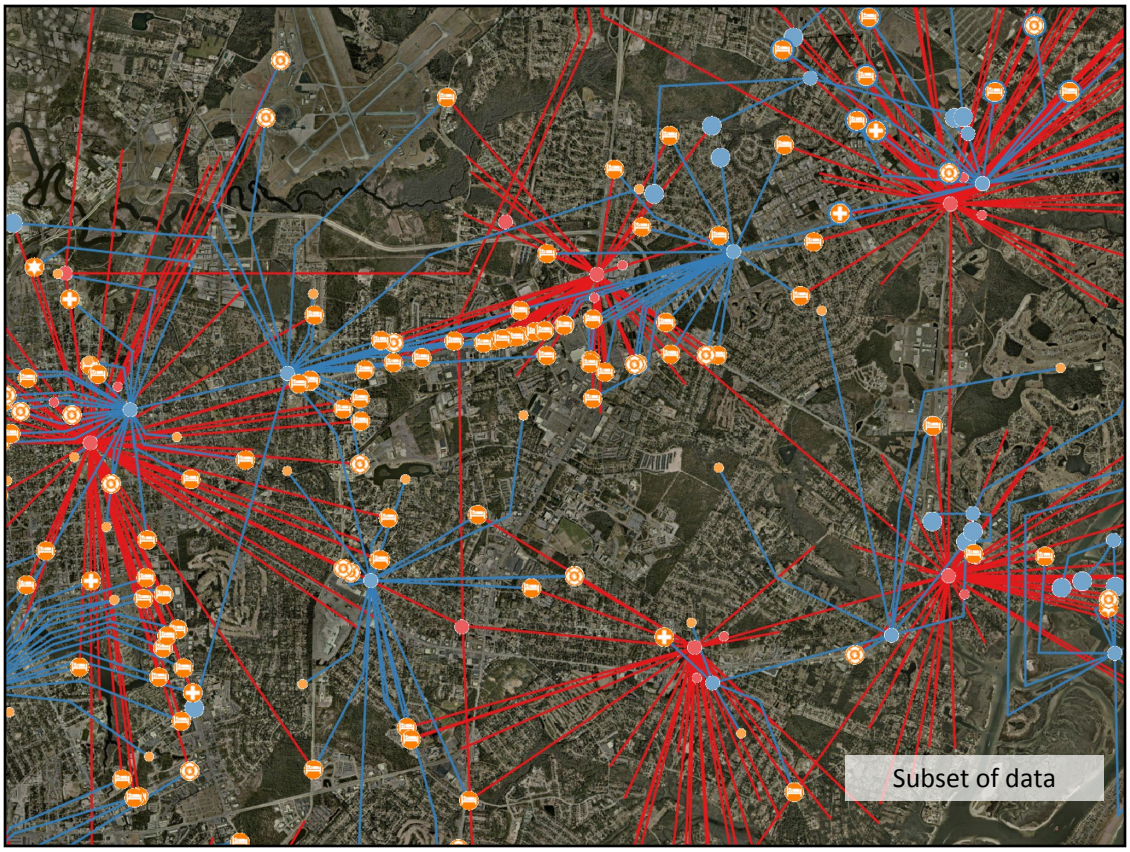
- Choose a scheme appropriate for:
  - sequential, qualitative, or diverging data
  - Diverging data & color schemes is particularly interesting
  - Are there more than 12 classes?
- Would prefer to start with 1 color, then build a scheme around it (like some website color design apps)
- 3 perceptual dimensions of color are hue, saturation and lightness
- cartographers seldom use more than seven classes on a choropleth map
- Idea: Combine colorbrewer.org & “choose the right graph” into one tutorial!
- Unfortunate undergrad who had to evaluate all 385 schemes usability
- User study was not scientific, unsolicited feedback only, possibly biased
- Paper motivation could be stronger
- Online tools:
  https://kuler.adobe.com/
  http://www.checkman.io/please/
  http://paletton.com/
  http://colorbrewer2.org/
  http://www.colourlovers.com/

- Why are color space conversions not identical? Isn't there a standard?
- Simultaneous Contrast Problem** avoid optical illusion
- Program looks like a(n effective) teaching tool
- Nice emphasis on UI (user interface: how the interface is laid out)/UX (user exerience: how the product feels)
- Gradients vs. flat colors?
- Limited # of colors means data will be compressed away
- Writing Comments
  - Read like a user guide not a paper
  - light on technical details
  - Was a justification of a user interface more than an academic paper?
  - Title: Color vs Colour? Pick one
  - Paper seemed intuitive, frequently states the obvious
- Paper a bit dated, but website is still maintained and is current
- Flash praised… why did it (was it forced to) go away?

Emergency Response Decision Making




Full network detail is overwhelming


Subset of data

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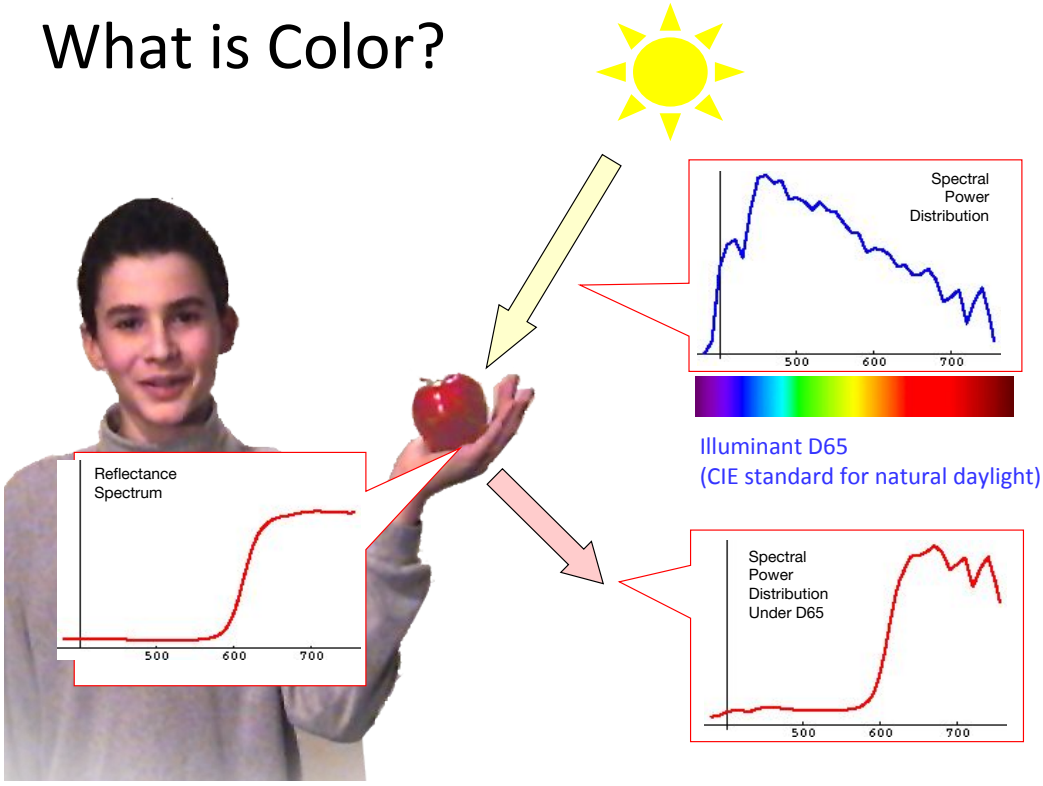
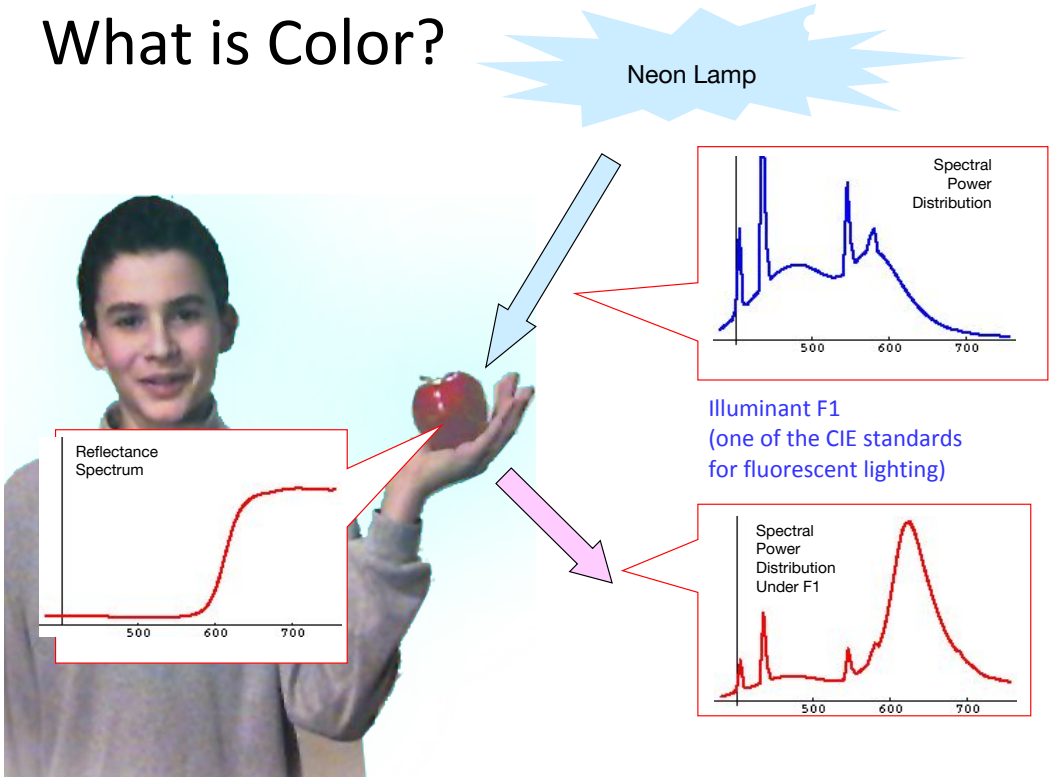
What is Color?

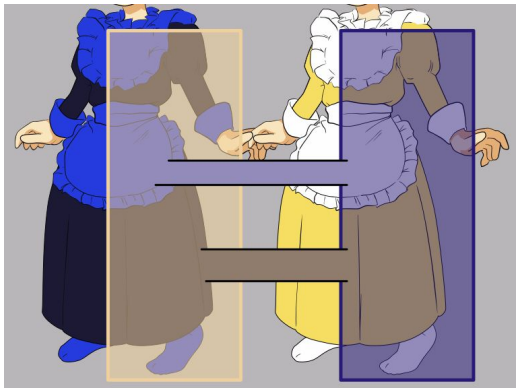


What is Color?



What color is the dress?

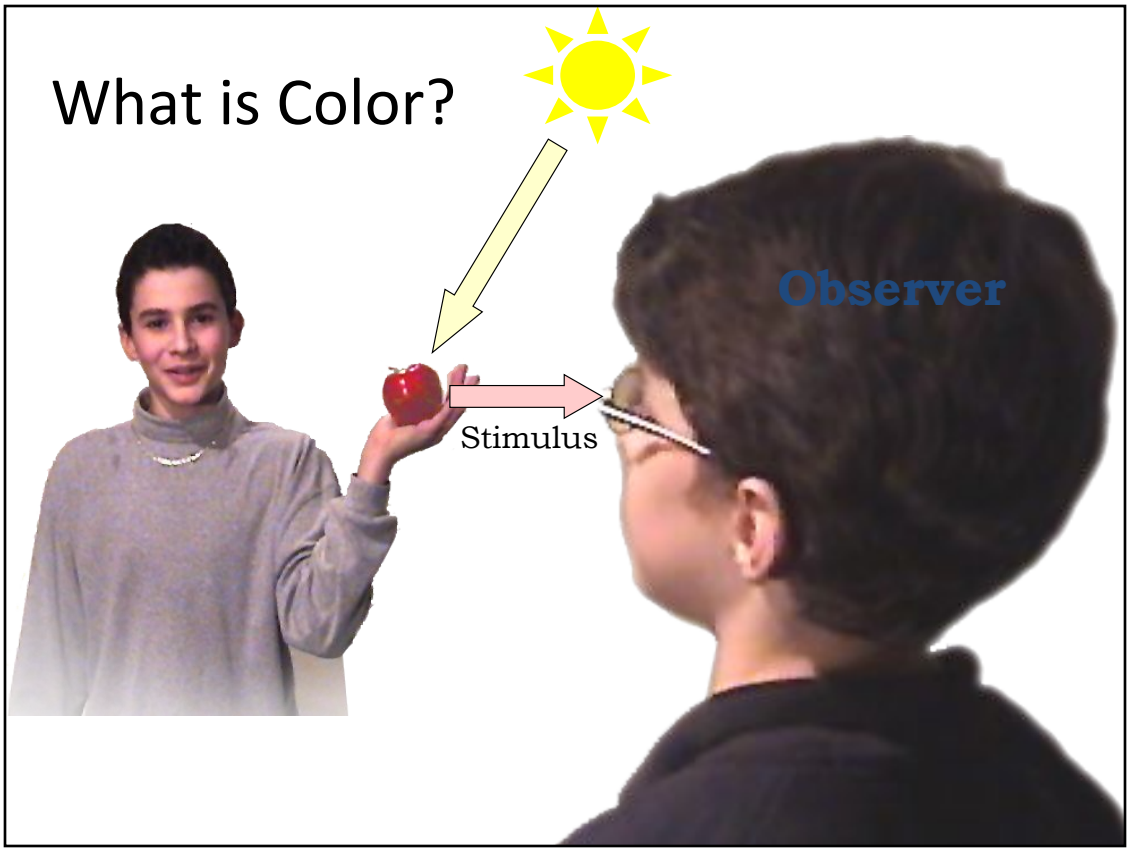
What does the viewer infer about the scene illumination?

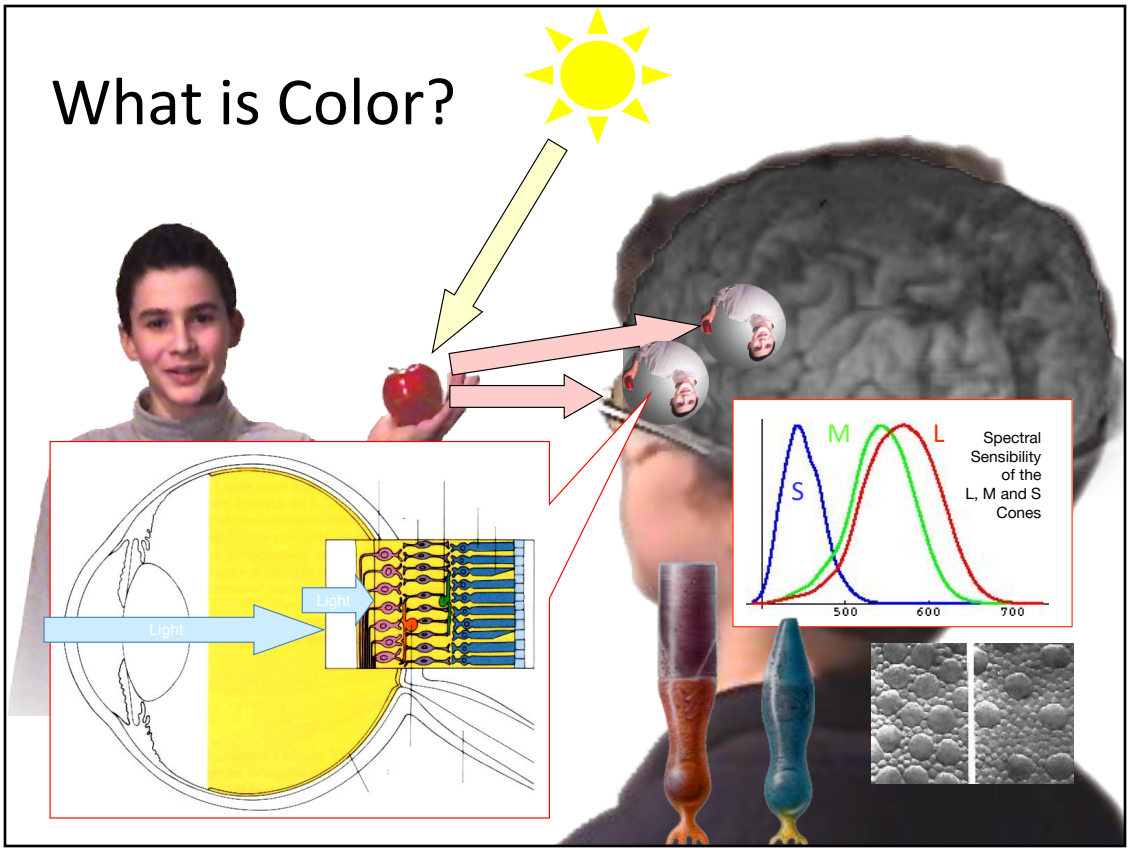


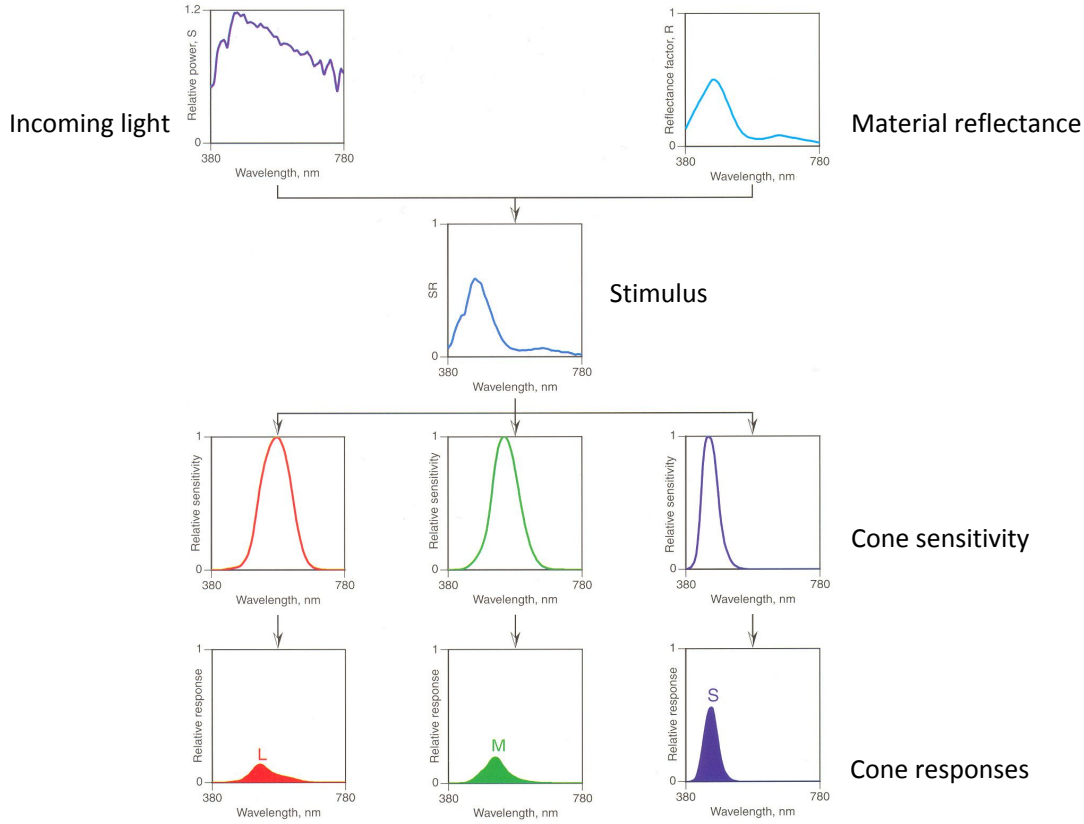
Blue & Black under yellow-tinted illumination?

White & Gold under blue tinted illumination?

https://en.wikipedia.org/wiki/The_dress

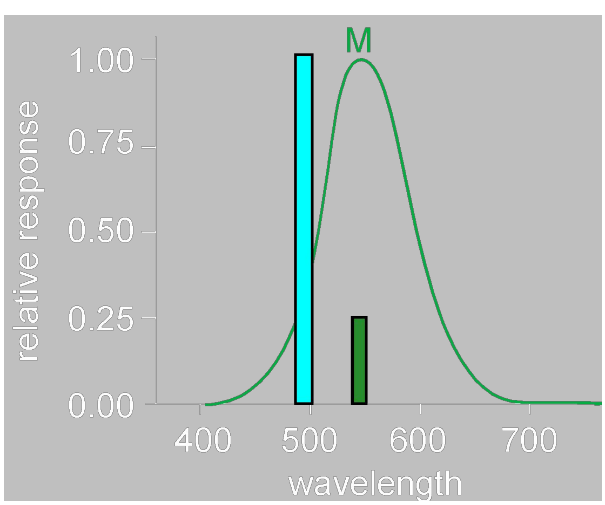

What is Color?
Observer
Stimulus


What is Color?
Light
Light
M
L
S
Spectral Sensibility of the L, M and S Cones
500
600
700



Cones do not "see" colors

- Different wavelength, different intensity
- Same response to a single cone

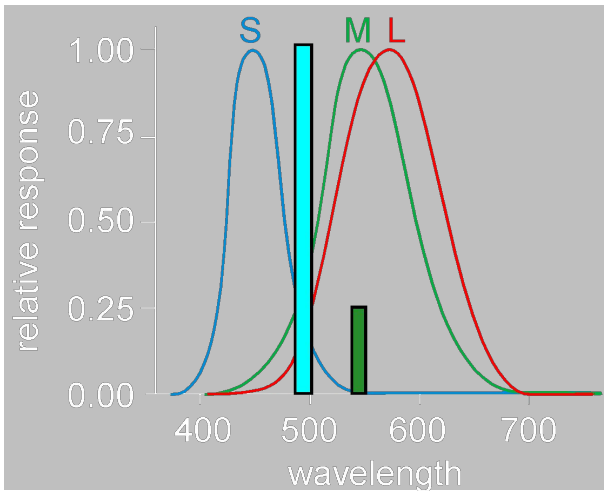


Dim green
Cone G: 0.25

Bright cyan
Cone G: 0.25

Response Comparison

- Different wavelength, different intensity
- But different response for different cones

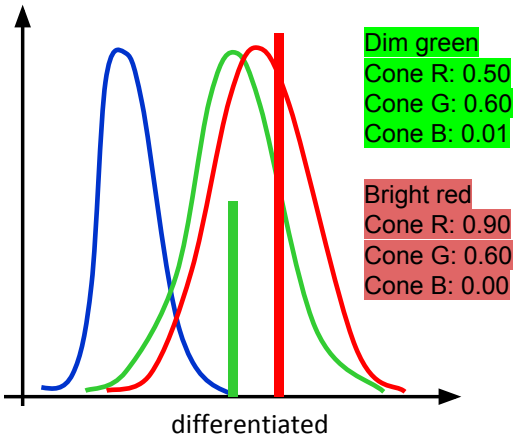


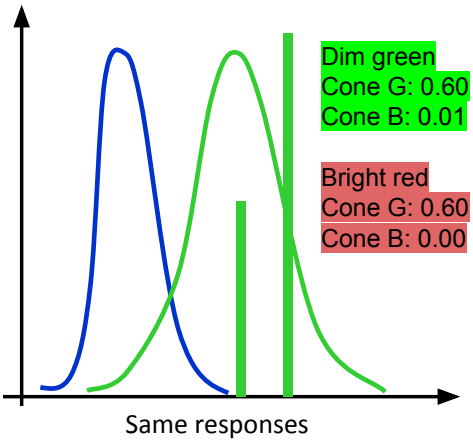
Dim green
Cone R: 0.20
Cone G: 0.25
Cone B: 0.01

Bright cyan
Cone R: 0.20
Cone G: 0.25
Cone B: 0.25

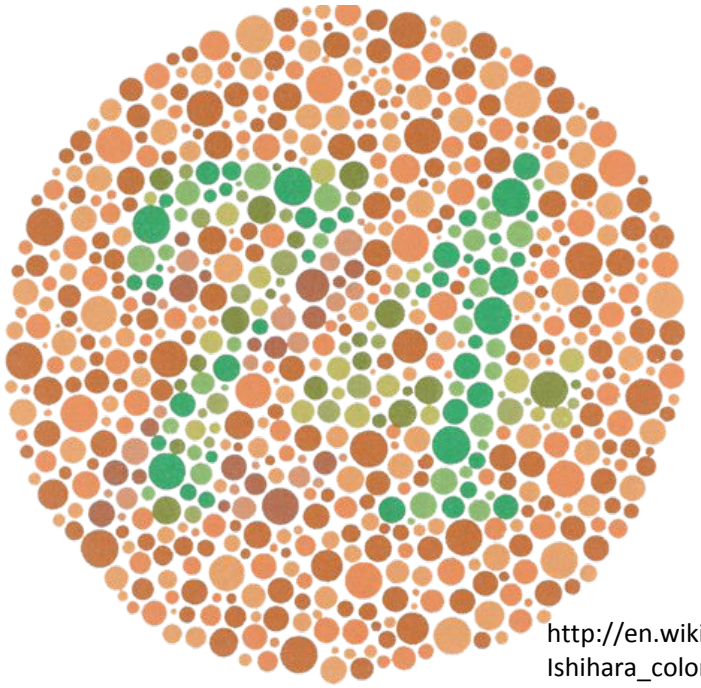
Color Blindness

- Classical case: 1 type of cone is missing (e.g. red)
- Now Project onto lower-dim space (2D)
- Makes it impossible to distinguish some spectra



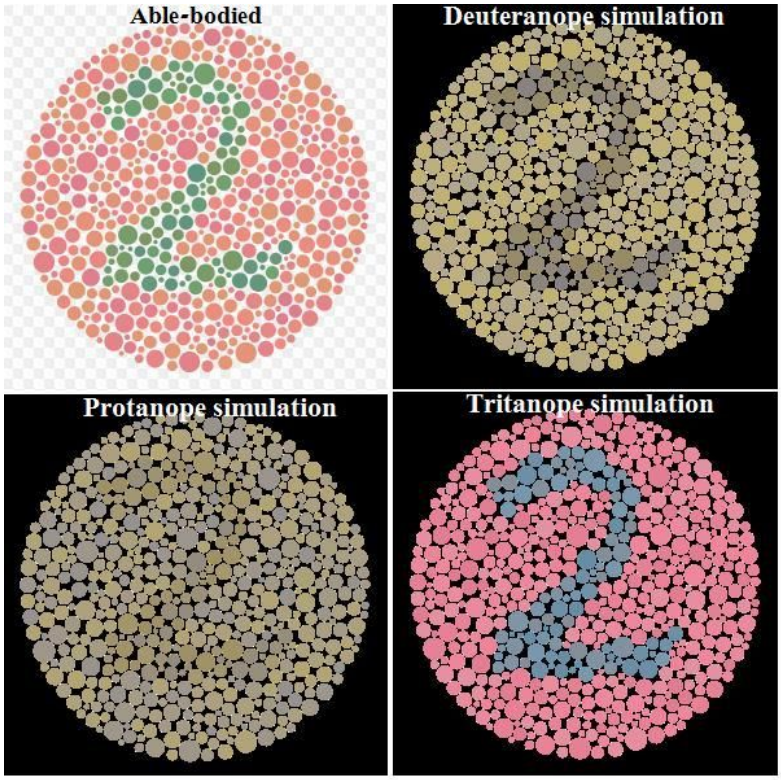


Ishihara Color Blindness Test



http://en.wikipedia.org/wiki/Ishihara_color_test

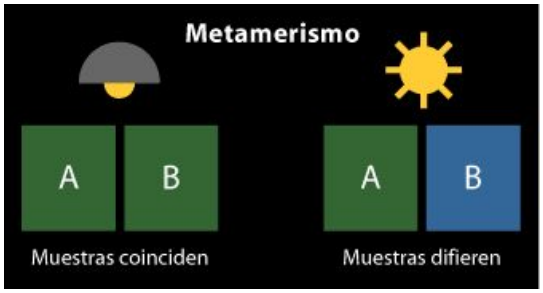
- Deuteranopia: missing green cone
- Protanopia: missing red cone
- Tritanopa: missing blue cone (rare)



http://en.wikipedia.org/wiki/File:Ishihara_compare_1.jpg

Metamerism: Apparent Matching

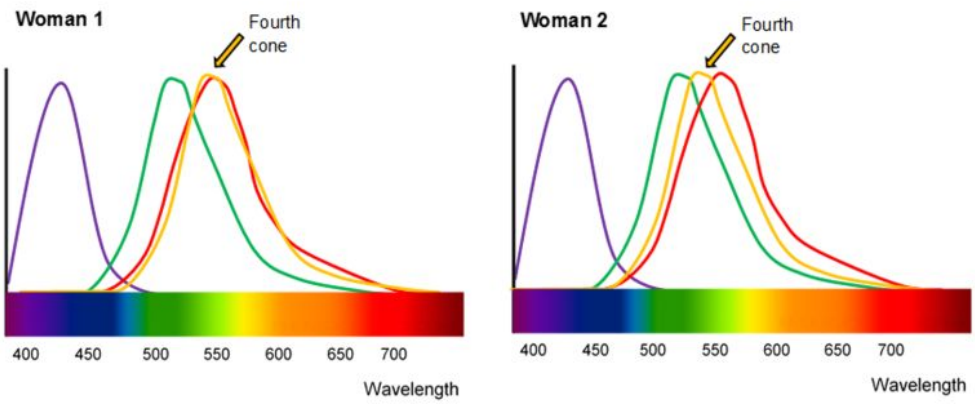
- When two materials look the same under one lighting condition (a coincidence), but look different under another:



http://gusgsm.com/metamerismo

- Remember that different spectral distribution of input light yield different visual stimuli
- We all experience some color blindness

Tetrachromacy: 4 cones?!



Often it is only a slight mutation of the red or green cone (left diagram), and thus not be easily detectable by a vision test or enable enhanced color vision.

https://theneurosphere.com/2015/12/17/the-mystery-of-tetrachromacy-if-12-of-women-have-four-cone-types-in-their-eyes-why-do-so-few-of-them-actually-see-more-colours/

Glasses to “correct” Colorblindness?

- Enchroma is not a cure for color blindness.
- Results vary depending on the type and extent of color vision deficiency.
- Enchroma does not endorse use of the glasses to pass occupational screening tests such as the Ishihara test.

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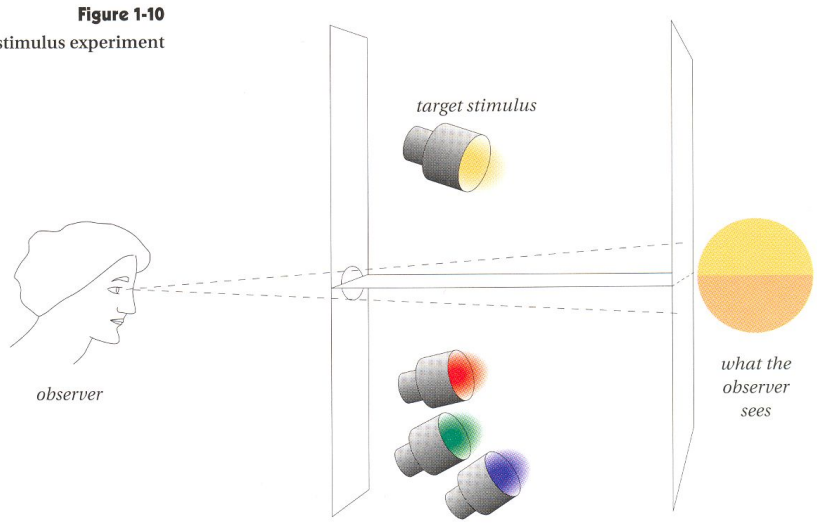
Standard Color Spaces

- Colorimetry: Science of color measurement
- Quantitative measurements of colors are crucial in many industries
  - Television, computers, print, paint, luminaires
- Naive digital work uses a vague notion of RGB
  - Unfortunately, RGB is not precisely defined, and depending on your monitor, you might get something different
- We need a principled color space…

CIE Color Matching Experiments

Figure 1-10
Tristimulus experiment



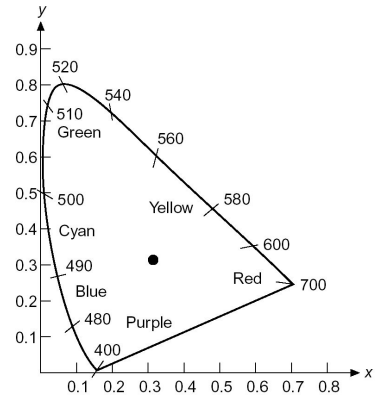
The observer adjusts the intensities of the red, green, and blue lamps until they match the target stimulus on the split screen.

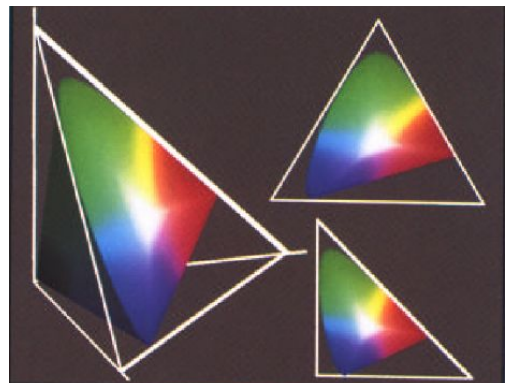
CIE XYZ Color Space

- Can think of X, Y , Z as coordinates
- Linear transform from typical LMS or RGB
- Note that many points in XYZ do not correspond to visible colors!

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.24 & -1.54 & -0.50 \\ -0.97 & 1.88 & 0.04 \\ 0.06 & -0.20 & 1.06 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

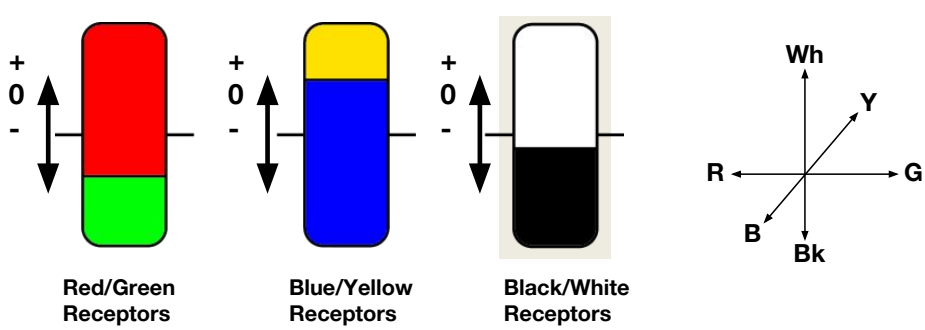
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.41 & 0.36 & 0.18 \\ 0.21 & 0.72 & 0.07 \\ 0.02 & 0.12 & 0.95 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$





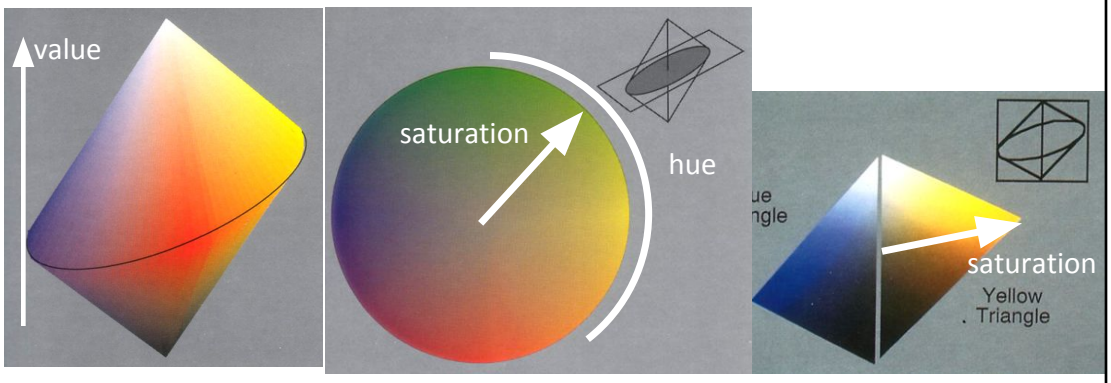
Hering 1874: Opponent Colors

- Hypothesis of 3 types of receptors: Red/Green, Blue/Yellow, Black/White
- Explains well several visual phenomena



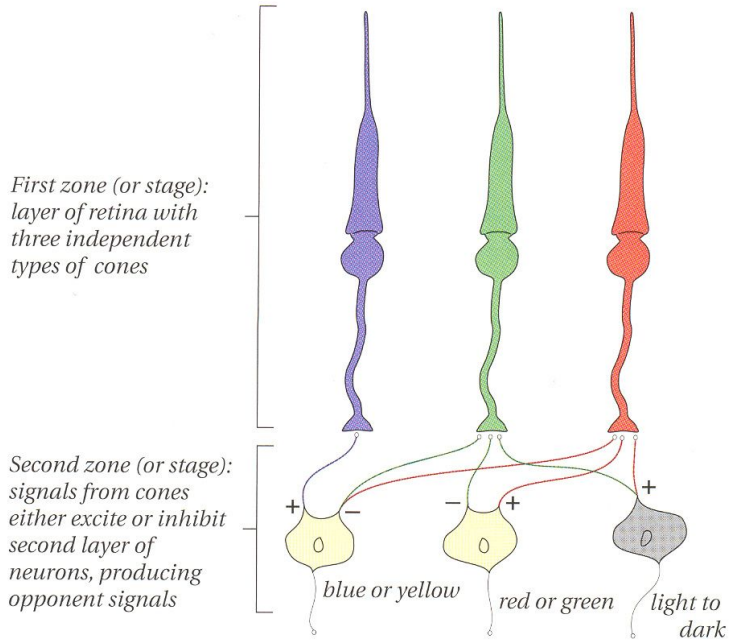
Hue Saturation Value (HSV)

- Value: from black to white
- Hue: dominant color (red, orange, etc)
- Saturation: from gray to vivid color



Color Opponents "Wiring"

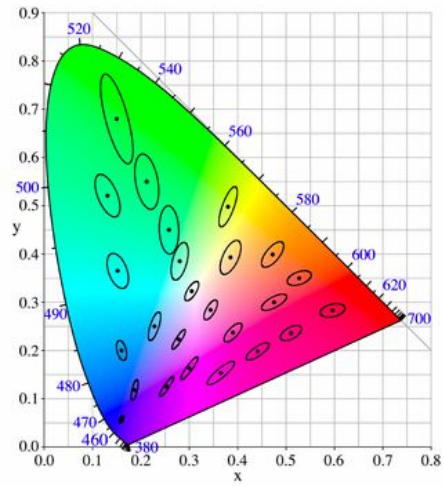
- Sums for brightness
- Differences for color opponents
- It's just a 3x3 matrix to convert HSV from/to LMS, RGB, or XYZ



Linear Color Spaces: RGB/XYZ/YPbPr

- Equal steps in linear color spaces do not correspond to equal differences for human perception
- MacAdam ellipses visualize the lack of perceptual uniformity [MacAdam 1942]

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R_{\text{linear}} \\ G_{\text{linear}} \\ B_{\text{linear}} \end{bmatrix}$$



http://en.wikipedia.org/wiki/File:CIExy1931_MacAdam.png

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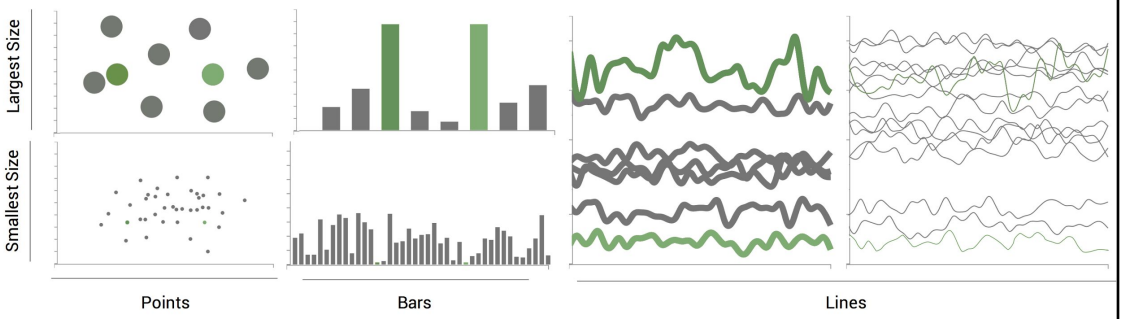
Reading for Tuesday: *(choose one)*

"Modeling Color Difference for Visualization Design"
Szafir, IEEE TVCG / IEEE VIS 2017



Reading for Tuesday: *(choose one)*

"Hue-Preserving Color Blending"
Chuang, Weiskopf, and Möller, TVCG 2009

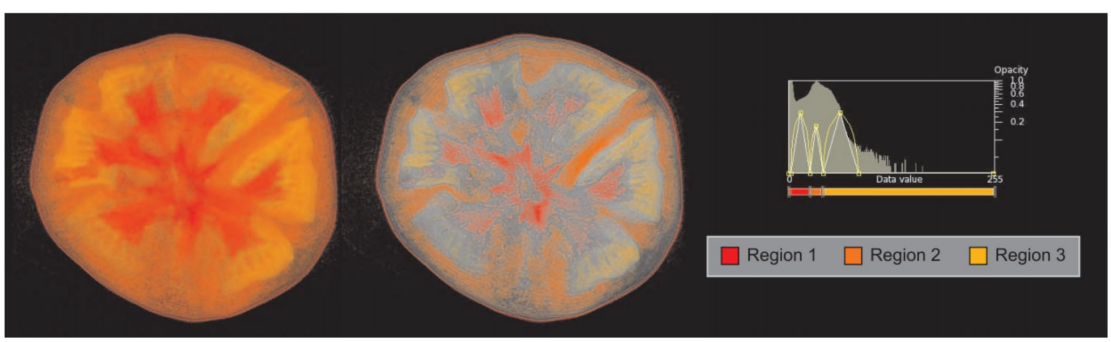


Fig. 1. Volume rendering of a tomato data set using traditional (left) and hue-preserving (middle) color blending. The data histogram, transfer function, and color legend are shown on the right.

Reading for Tuesday: *(choose one)*

"A Linguistic Approach to Categorical Color Assignment for Data Visualization", Setlur and Stone, IEEE InfoVis 2015

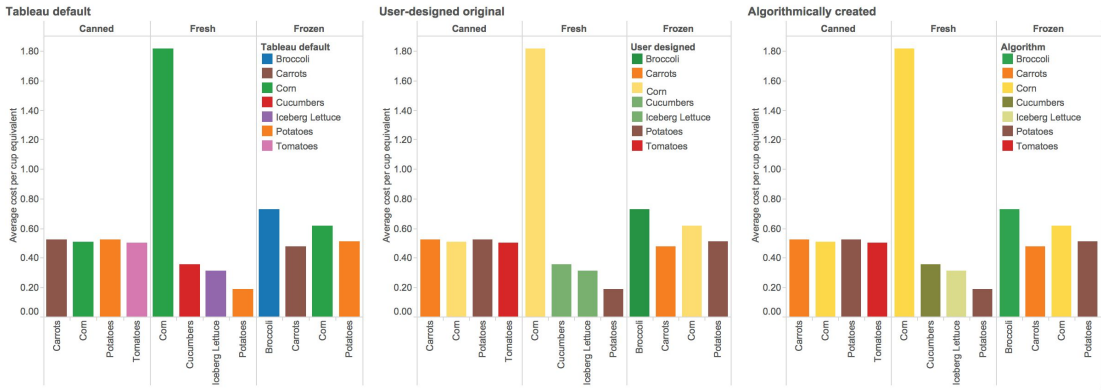


Fig. 1. This visualization was taken from a Tableau Public workbook [11] to illustrate the value of semantic color encoding. Left: The Tableau default colors are perceptually legible, but conflict with the data semantics ('Tomatoes' are pink, 'Corn' is green). Center: The Tableau author matched the colors to the data semantics (red for 'Tomatoes', yellow for 'Corn'), which makes it easier to identify the different types of vegetables in the graph. Right: Our algorithm automatically created a similarly effective result.

Homework Assignment 5: Experimenting with Color

- Revisit an earlier assignment/data/toolkit
  - Make a non-color-related improvement to this visualization
- Prepare many versions of the same visualization experimenting with different color palettes, e.g.:
  - Shades of grey
  - Black & white
  - Cool vs. warm tones
  - Bold/saturated vs. pastel
  - Colorblind aware
  - Light vs dark background and/or color negation
  - Etc.
- Analyze the effectiveness of the color scheme for each visualization.
  - How well does it convey the message? Or mislead the viewer?
- Compare the visualizations to each other.

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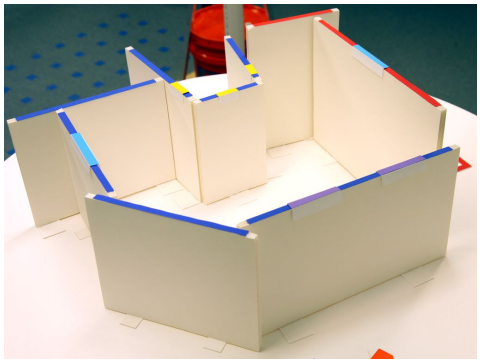
Spatially Augmented Reality (SAR) Projection

camera detects design geometry

6 projectors augment design

design sketched with foam-core walls

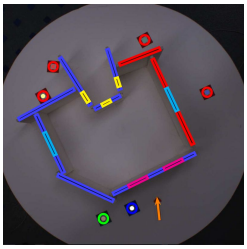
Tangible Interface for Architectural Design



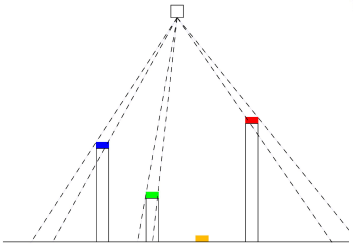
Exterior & interior walls

Tokens for:

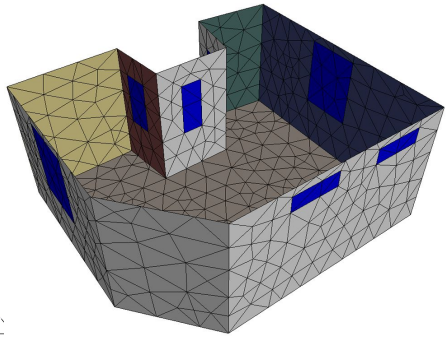
- *Windows*
- *Wall/floor colors*
- *North arrow*



Overhead camera



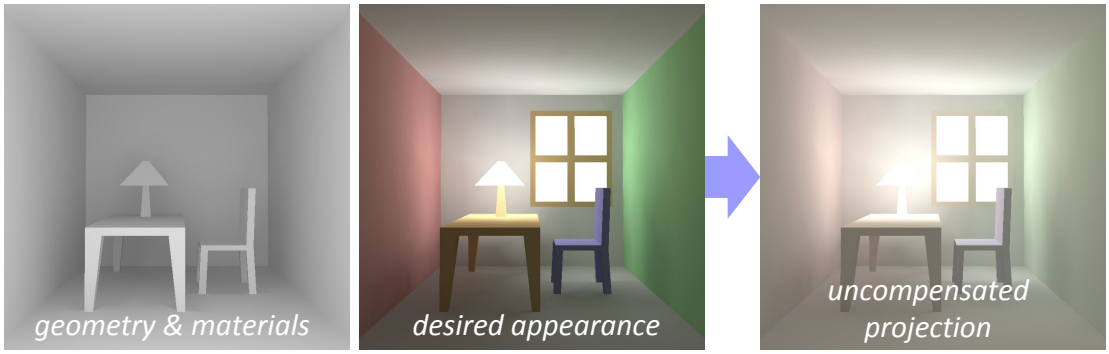
Projection geometry



Inferred design

[redacted]

Motivation:



Can we do a better job reproducing the desired appearance?

Related Work: Radiometric Compensation

- Minimize artifacts caused by light modulation with local surface [Bimber et al. 2005; Nayar et al. 2003; Grundhöffer & Bimber 2008]
- Does not consider global light inter-reflection

Grundhöffer & Bimber 2008

Our Problem Statement

- Known scene geometry
- Known surface reflectances, *all ideal diffuse*
- Fixed, calibrated projectors
- Given:

  Desired target surface appearance (texture) for each physical surface
- Solve for:

  Projection texture for each physical surface that most faithfully reproduces the desired appearance

Related Work: Reverse Radiosity

- Forward lighting with radiosity

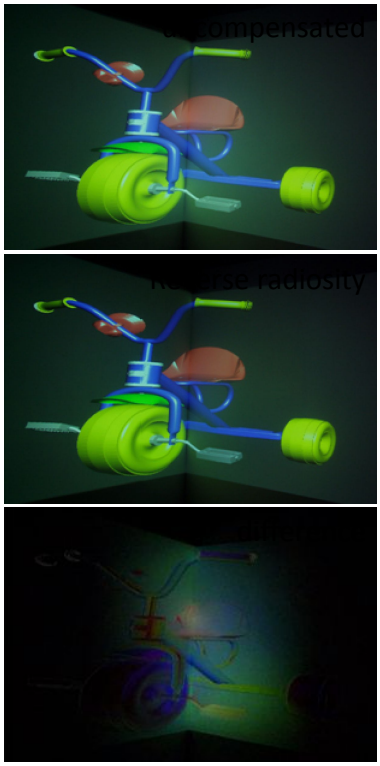
$$B = (I - F)^{-1} E$$

values for rendering — *form factor matrix* — *direct light*

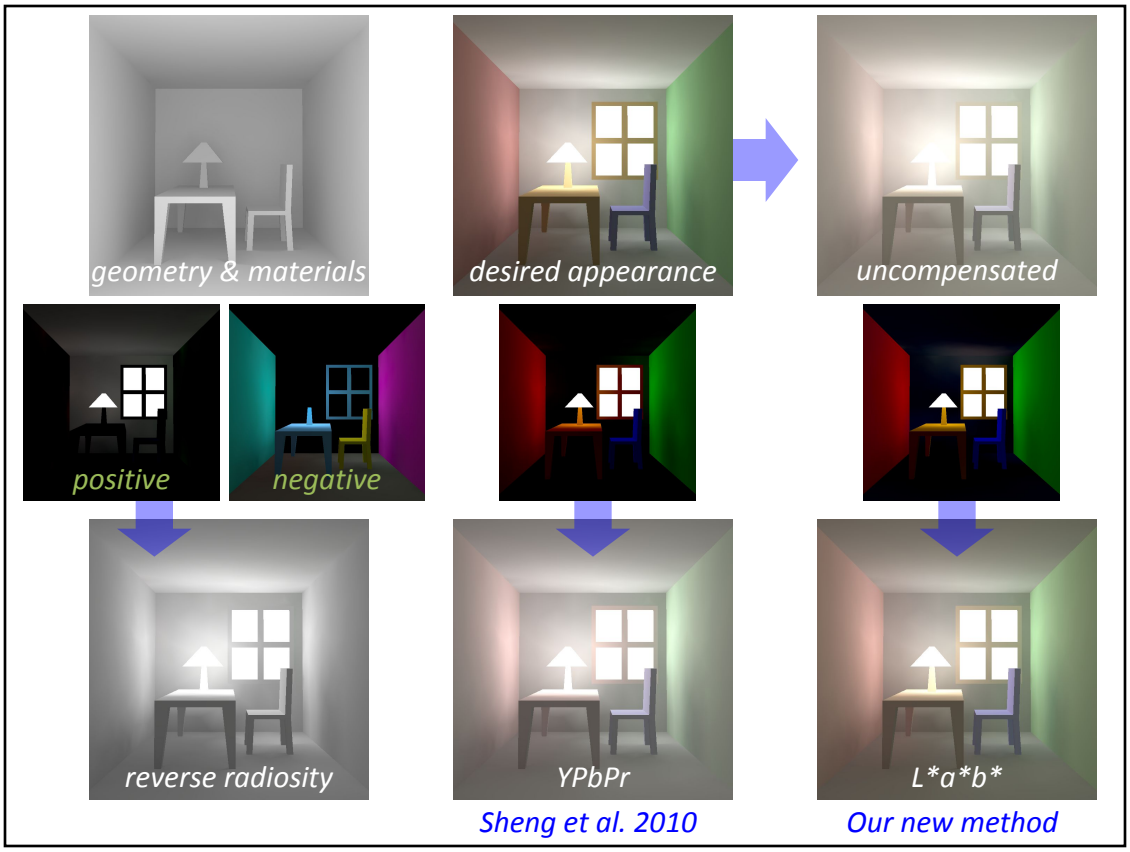
- Inverse lighting with radiosity: Reverse Radiosity (RR)
  - [Bimber et al. 2006]

$$E = (I - F) B$$

projection values — *desired appearance*



Bimber et al. 2006



L*a*b*: a perceptual color space

Designed to match human color perception data

$$\begin{array}{r} \textit{intensity} \\ \textit{red-green} \\ \textit{yellow-blue} \end{array} \begin{bmatrix} L \\ a \\ b \end{bmatrix} = \begin{bmatrix} 116h(\frac{Y}{Y_n}) - 16 \\ 500\left(h(\frac{X}{X_n}) - h(\frac{Y}{Y_n})\right) \\ 200\left(h(\frac{Y}{Y_n}) - h(\frac{Z}{Z_n})\right) \end{bmatrix}$$

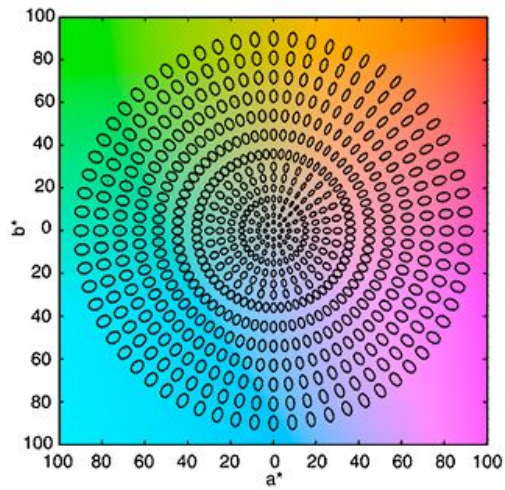
$$h(t) = \begin{cases} t^{\frac{1}{3}} & t > (6/29)^3 \\ \frac{1}{3}(\frac{29}{6})^2 t + \frac{4}{29} & \text{Otherwise} \end{cases}$$

L*a*b* is nonlinear, a challenge for optimization

Quantitative Perceptual Comparison

- $$\Delta E = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2}$$

- Where 2.3 ΔE = JND (just noticeable difference)
- The MacAdams ellipses are more equal size circles in L*a*b*



http://w3.kcua.ac.jp/~fujiwara/infosci/ellipses_lab.png

Our Optimization Formulation

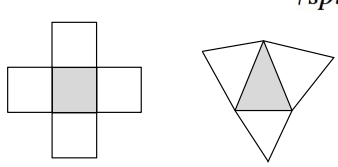
desired appearance *projection result*

Absolute Error:

$$\phi_{abs} = \frac{\sum_i A_i[(L_i - L_i')^2 + (a_i - a_i')^2 + (b_i - b_i')^2]}{A_{avg}}$$

Spatial Error:

$$\phi_{spt} = \sum_{(i,j)\in nbd} [(L_i - L_j) - (L_i' - L_j')]^2 + [(a_i - a_j) - (a_i' - a_j')]^2 + [(b_i - b_j) - (b_i' - b_j')]^2$$



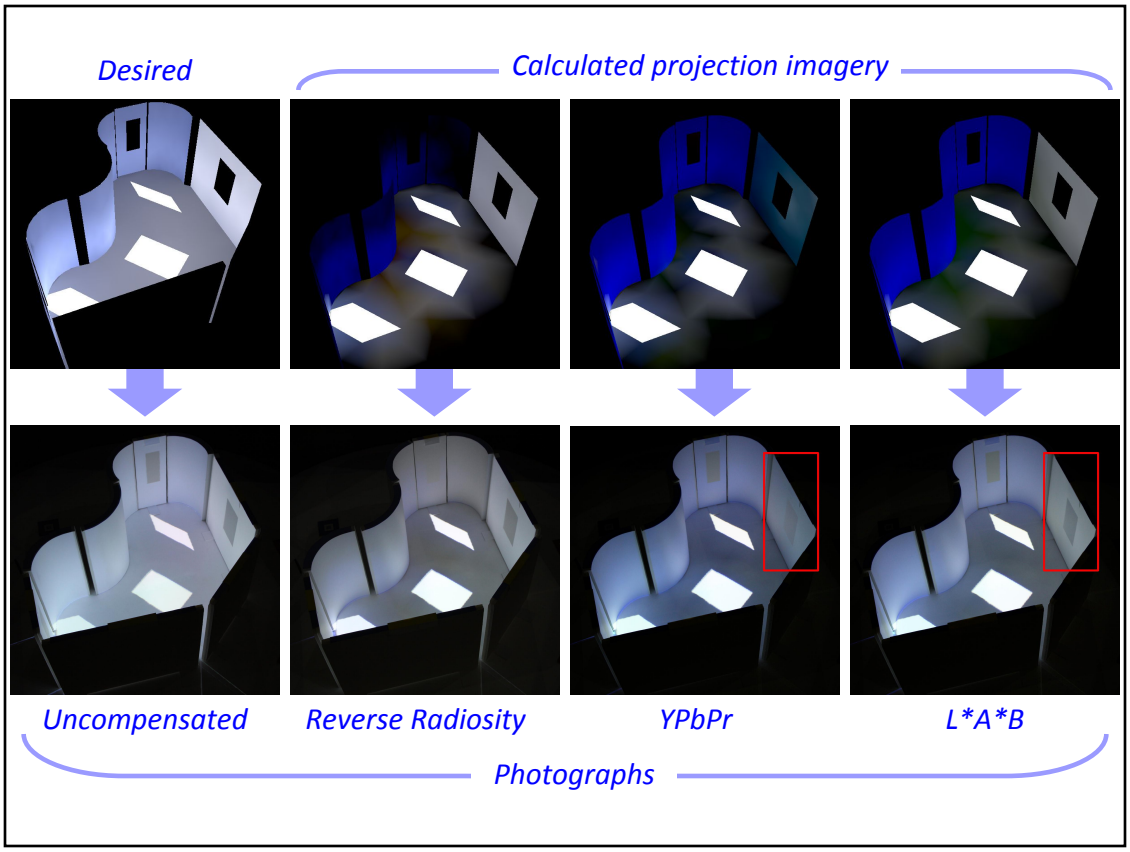
gradient in desired appearance *gradient in projection result*

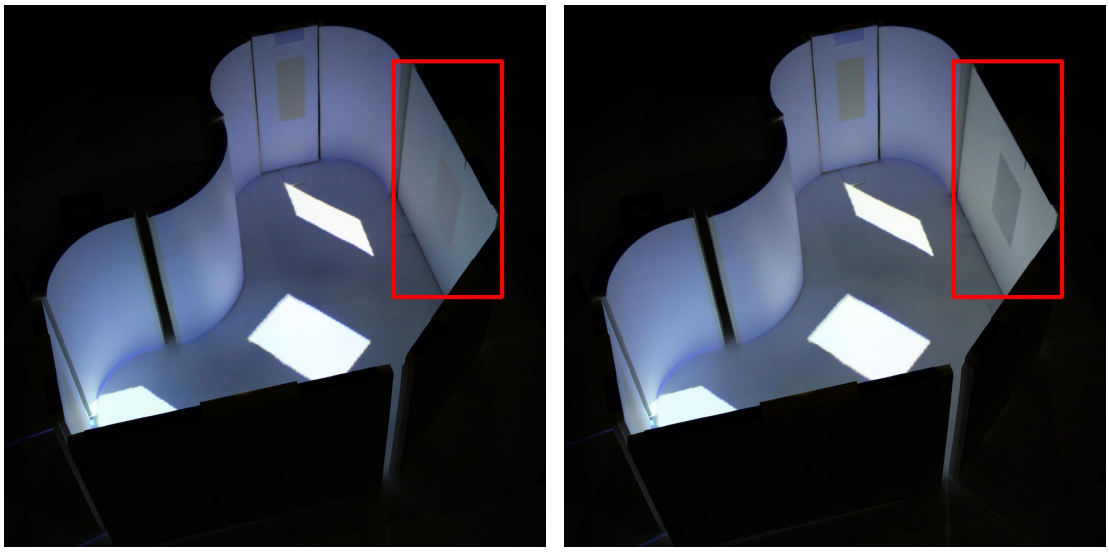
Complete Objective Function: $\phi = \alpha\phi_{abs} + (1-\alpha)\phi_{spt}$

We use α = 0.9

Box constraints:

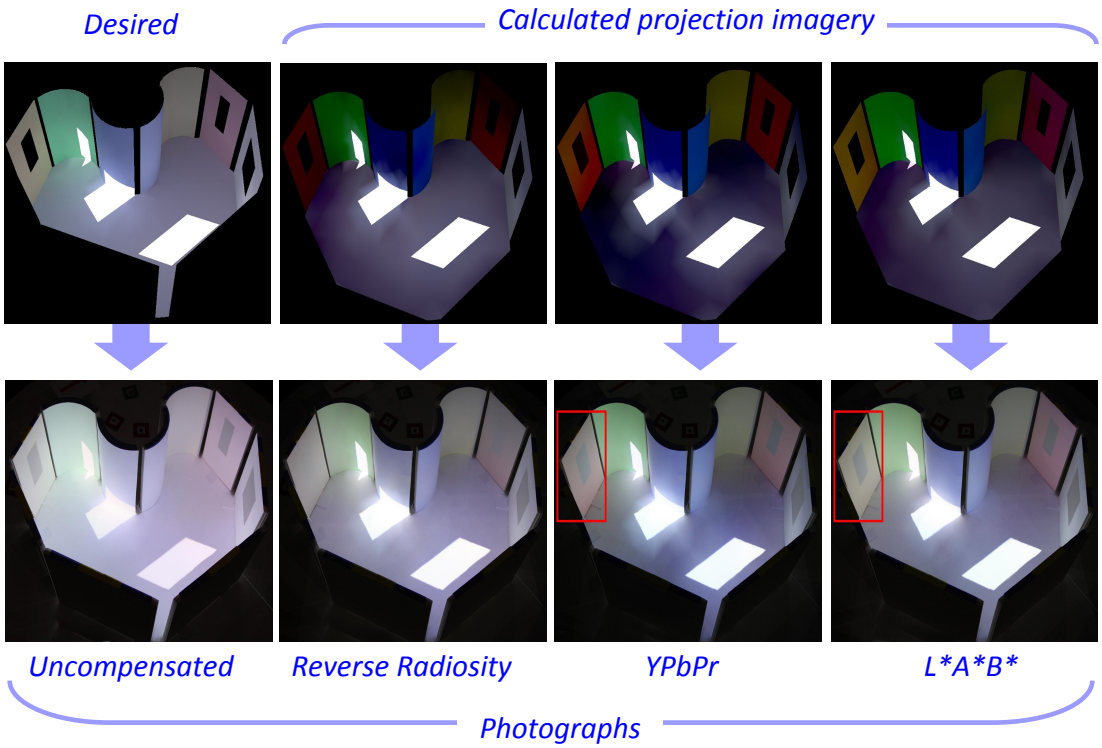
minimum & maximum brightness of projector system

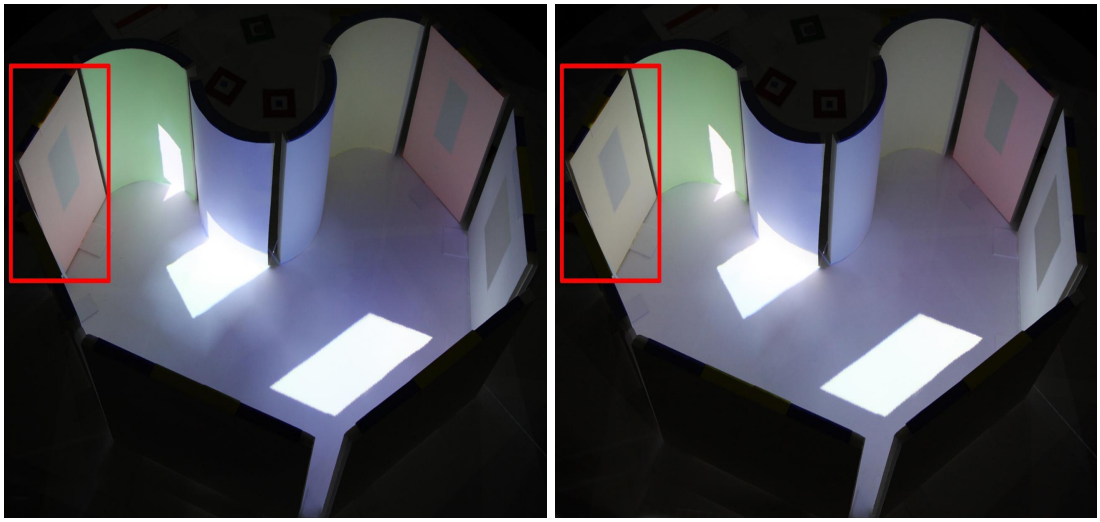




Sheng et al. 2010
Optimized in YPbPr space

New method
Optimized in L*A*B space





Sheng et al. 2010
Optimized in YPbPr space

New method
*Optimized in L*A*B space*

"Perceptual Global Illumination Cancellation in Complex Projection Environments"
Yu Sheng, Barbara Cutler, Chao Chen, and Joshua Nasman
Eurographics Symposium on Rendering (EGSR), June 2011.